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SEISMOMAGNETIC EFFECT GENERATED BY THE OCTOBER 18, 1989, M_L 7.1 LOMA PRIETA, CALIFORNIA, EARTHQUAKE

R. J. Mueller and M. J. S. Johnston

U. S. Geological Survey, Menlo Park, California

Abstract. A differentially connected array of proton magnetometers operated within the epicentral region of the October 18, 1989, M_L 7.1 Loma Prieta earthquake for 12 years from 1974 to 1986. The closest magnetometer station was located 7.3 km from the epicenter of the earthquake and within 3 km of the site where anomalous ULF magnetic noise measurements were observed. Following the earthquake, the magnetometers were reinstalled with sensors replaced in the original undisturbed sensor holders. Comparison of pre-1986 total intensity magnetic field data with data obtained during the months following the earthquake indicate local offsets of about 1 nT may have been generated at stations nearest the epicenter. Tests on other continuous differenced data from 1983 to present indicate that offsets determined could be biased by as much as 0.7 nT. The offsets can be approximately fit with a simple seismomagnetic model of the earthquake for which 1.9 m of right lateral and 1.3 m of dip slip (southwest side up) occurred on a fault patch between 6 km and 18 km deep and 45 km long. The total rock magnetization is assumed to be 1.5 A/m. Since the offset has persisted following the earthquake, an alternate explanation in terms of electokinetic effects is unlikely even though transient ground water flow occurred following the earthquake. Comparison of pre-1986 and similar post-seismic total magnetic field noise does not indicate any change caused by aliasing of ULF (0.01 Hz - 10 Hz) magnetic noise in the vicinity of the Loma Prieta earthquake.

Introduction

Stress changes that accompany seismic failure are expected to cause piezomagnetic effects and consequent time-dependent local magnetic anomalies (*Stacey*, 1964; *Nagata*, 1970). Local magnetic field changes accompanying moderate to large earthquakes have been observed and actively sought in regions subject to earthquake hazards (*Breiner*, 1967; *Smith and Johnston*, 1976; *Rikitake*, 1980; *Honkura*, 1982; *Shapiro*, 1982; *Davis and Johnston*, 1983; *Johnston and Mueller*, 1987). A coseismic magnetic field change or seismomagnetic effect should result from piezomagnetic effects generated by the earthquake-related changes in the local stress field. This paper reports possible magnetic field offsets generated at sites located near the Loma Prieta earthquake and the physical implications of these offsets.

Installation

The U. S. Geological Survey operated a network of magnetometer stations in central California near the epicentral region of the Loma Prieta earthquake from 1974 to 1986 in an effort to detect local magnetic field perturbations. Figure 1 shows locations of magnetometer stations in central California reoccupied after the Loma Prieta earthquake. The closest station EUC was 7.3 km from the epicenter of the earthquake. All stations use E. G. & G. Geometrics, Inc. model G-856 or G-826, proton precession magnetometers operated at 0.1 nT to 0.25 nT resolution. Data collected prior to 1986 were synchronously sampled (10 minute) and transmitted through a 16-bit digital telemetry system to Menlo Park, California (*Mueller, et. al.*, 1980). Post seismic data were recorded on site using four portable systems which were operated at the stations between October 19, 1989 and December 30, 1989 using a synchronous 15 minute sample interval. Instrument sensors were replaced in their original sensor holders to within 1 centimeter. Sensors at each stations are in local gradients less than 2 nT/m and errors resulting from replacement of the sensors are less than 0.02 nT.

Data

The magnetometer stations were not operational at the time of or during the 3-year period prior to the Loma Prieta earthquake so details of preseismic effects, if any, are not available. Since these data are obtained using drift-free magnetometers and are extremely stable with time, comparison of pre-1986 data with post-seismic data would allow identification of the net magnetic field offset that occurred with the earthquake. To isolate local magnetic field changes and reduce the effects of ionospheric and magnetospheric disturbances, synchronously sampled magnetic field data from pairs of sites are differenced.

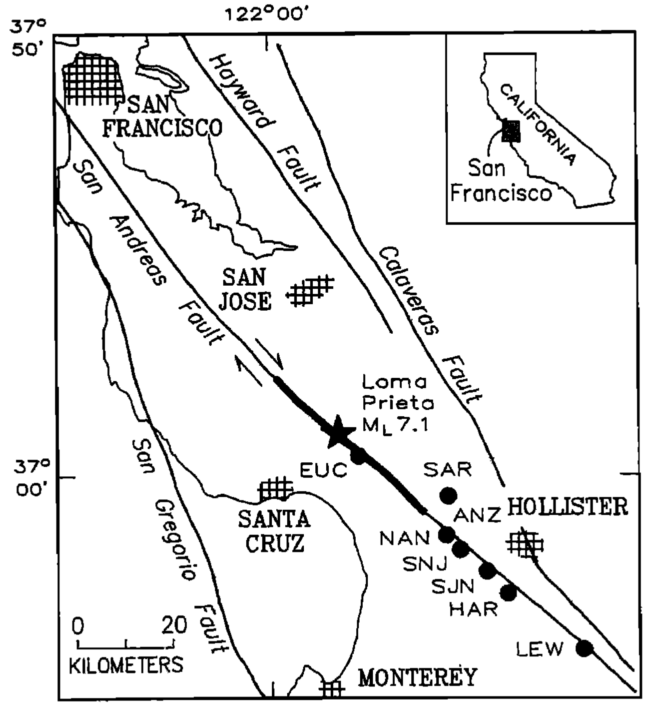

Fig. 1. Location of magnetometer stations relative to the epicenter ( ) of the Loma Prieta earthquake. The thickened San Andreas fault line indicates the rupture zone of the earthquake.

averaged, and secular variation is removed. Figure 2 shows plots of 3-day averages of data referenced to site SJN. Comparison of data collected prior to 1986 with the data obtained during the months following the earthquake indicate offsets between 0.1 nT and 1.4 nT (Table 1).

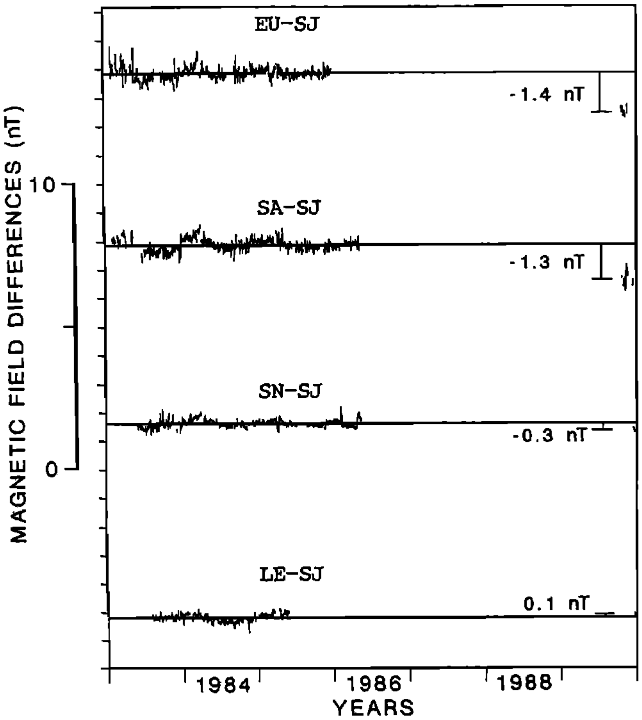

Fig. 2. Processed magnetic field data indicating offsets between pre-1986 and post-seismic data referenced to station SJN. All data are displayed with identical vertical scale, and plots from top to bottom represent increasing distance from the epicenter of the Loma Prieta earthquake.

TABLE 1: MAGNETIC FIELD OFFSETS REFERENCED TO STATION SJN

STATION	PREDICTED	OBSERVED	DIFFERENCE (OBS-PRED)	DISTANCE
EUC	−1.1 *nT*	−1.4 ± 0.2 *nT*	−0.3 *nT*	7.3 *km*
SAR	−1.4 *nT*	−1.3 ± 0.2 *nT*	0.1 *nT*	28.3 *km*
NAN	−0.5 *nT*	−1.1 ± 0.4 *nT*	−0.6 *nT*	30.9 *km*
ANZ	−0.5 *nT*	+0.1 ± 0.6 *nT*	0.6 *nT*	30.9 *km*
SNJ	−0.2 *nT*	−0.3 ± 0.1 *nT*	−0.1 *nT*	38.1 *km*
SJN	REFERENCE	REFERENCE	0.0 *nT*	41.9 *km*
HAR	+0.1 *nT*	−0.6 ± 0.1 *nT*	−0.7 *nT*	49.2 *km*
LEW	+0.2 *nT*	+0.1 ± 0.1 *nT*	−0.1 *nT*	68.2 *km*

Table 1. Predicted and observed values of total magnetic field changes, referenced to station SJN, as a function of distance from the epicenter of the Loma Prieta earthquake. Errors shown for the observed values are standard deviations of the pre-1986 data. All observed values are within 0.7 nT of the predicted values.

The largest observed changes occur at the stations located nearest the epicenter of the Loma Prieta earthquake. Standard deviations of these data range from 0.2 nT to 0.6 nT. To test this procedure of extrapolating from 1986 to 1989, continuous differenced data from pairs of stations with similar separations, but at large (>100 km) distances from the Loma Prieta region were subjected to identical processing using data over the same time period (1983 to present). Comparison of these data with, and without, the 3-year data gap indicate that offsets estimated in this manner could be biased by as much as 0.7 nT.

Discussion

Coseismic magnetic field offsets can result from piezomagnetic effects generated by an earthquake-related change in the local stress field. Estimates of the stress change from dislocation models of the earthquake have been combined with a seismomagnetic model to calculate the expected magnetic field change for the Loma Prieta earthquake. This model was constructed for an earthquake in which the strike, dip, depth, fault length, fault width and style of faulting were chosen to be consistent with the geodetically determined parameters (*Plafker and Galloway*, 1989) (Figure 3). Aeromagnetic data indicate a magnetic high located in the epicentral region of the Loma Prieta earthquake and this anomaly was inferred to be caused by buried plutonic rock similar to the gabbro exposed near station ANZ (*Hanna et al.*, 1972). Magnetic measurements of the gabbro exposed near station ANZ indicated magnetizations of 2 A/m to 3 A/m while other rock types in the region ranged from 0.01 A/m to 0.7 A/m. For modeling purposes, a value of 1.5 A/m was chosen to represent the average regional magnetization. The contours of calculated magnetic field change in nanotesla for this model are shown in Figure 3. The observed magnetic field offsets can be approximately fit by this seismomagnetic model of the earthquake (Table 1).

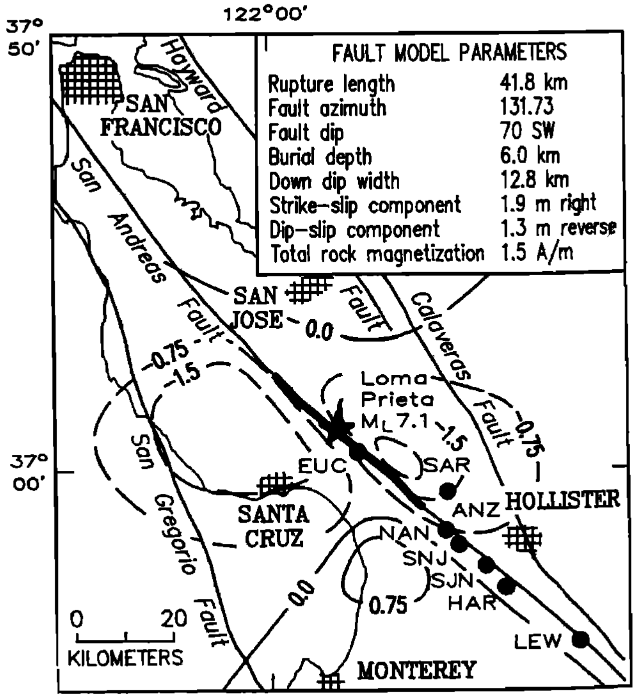

Fig. 3. Contours of calculated magnetic field (nanoteslas) expected from the Loma Prieta earthquake. Fault parameters used to model the event are shown in the upper right-hand corner.

An alternate explanation in terms of an electokinetic model is possible (*Fitterman*, 1979), but unlikely. The magnetic field offsets have remained invariant for several months, with no indication of decay as the ground water system stabilized. However, since some ground water flow did occur immediately following the earthquake, this process can not be completely ruled out.

Large amplitude electromagnetic fields, in the ultra-low frequency (ULF) range 0.01 Hz to 10 Hz, were observed near the epicenter of the Loma Prieta earthquake (Fraser-Smith et. al., 1990). The changes were observed both before and have continued after the earthquake. The ULF magnetic field measurements were obtained at a location approximately 3 km south of station EUC and about the same distance from the hypocenter. The proton precession magnetometers operated in the U.S.G.S. network have a ten-minute sample interval, measure total magnetic field intensity (least count 0.1 nT), and are not designed to monitor magnetic field fluctuations at frequencies between 0.01 Hz and 10 Hz. However, due to aliasing (*Bendat and Piersol*, 1966), the effect of 0.5 nT to 4 nT (*Fraser-Smith*, personnel comm., 1990) increases in ULF magnetic field noise could increase the apparent short period background noise level recorded on the precession magnetometers.

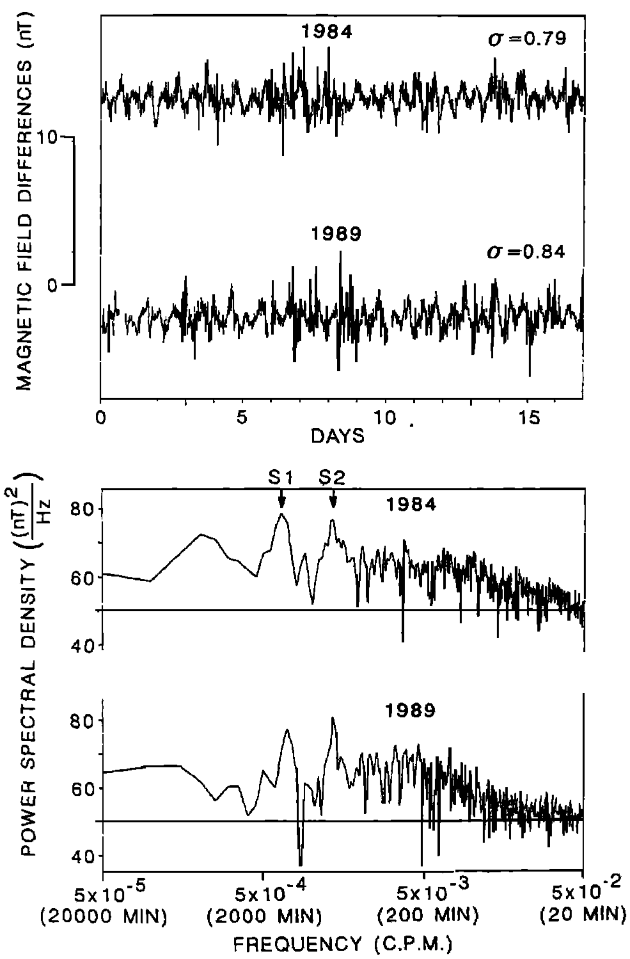

Fig. 4. Comparative seventeen day sections of magnetic field data from station EUC referenced to station SJN during 1984 and 1989 (upper plots). Standard deviations of the 1984 and 1989 data are 0.79 nT and 0.84 nT, respectively. The bottom two plots show power spectra calculated from these data. The 95% confidence limits are 12.1 db and -5.1 db. The dominant power in these data is at the S_1 and S_2 solar spectral peaks.

To search for increases in background noise in the total magnetic field intensity at station EUC, a 17 day section of data from 1984 was compared with a similar section in 1989 after the Loma Prieta earthquake. Both sections contain data with similar levels of solar disturbance activity. Figure 4 (top) shows data plots of magnetic field intensity for station EUC referenced to station SJN. Figure 4 (bot) shows plots of power spectra obtained from the two sections of data. Both the differenced data plots and the power spectra do not indicate any significant differences between total magnetic field in 1984 compared to the data collected after the Loma Prieta earthquake. Unfortunately, total magnetic field data during the time period of the largest observed ULF magnetic field changes (3 hour period prior to the earthquake) are not available.

Conclusions

Two physical mechanisms could explain the seismomagnetic effects recorded after the October 18, 1989, Loma Prieta M_L 7.1 earthquake: (1) the seismic stress drop causes piezomagnetic effects and consequent local magnetic field changes or (2) there were substantial electric currents generated rapidly by either rupture-driven charge-generation mechanisms or by earthquake-driven fluid flow (electrokinetic effects). The persistence of the changes for periods of months since the earthquake and the highly conductive nature of the earth's crust appear to preclude electrokinetic effects as primary physical mechanisms driving these changes. The observations are generally consistent in amplitude and sense with a reasonable seismomagnetic model of the event. Observed increases in ULF magnetic field noise near the epicenter of the Loma Prieta earthquake were not detected in the total magnetic field measurements.

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R. J. Mueller and M. J. S. Johnston, U.S. Geological Survey, Menlo Park, Ca. 94025

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